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Impact of conservation tillage on nitrogen and phosphorus runoff losses in a potato crop system in Fuquene watershed, Colombia.

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ABSTRACT

Intensive tillage (IT) in potato crops is considered as one of the main non-point sources (NPS) of local water eutrophication in the Fuquene Lake of Colombia. Therefore, the local government has invested in several programs aiming at the adoption of principles of conservation tillage (CT) which would allow for developing and applying the agricultural best management practices (BMPs). The complexity of hydrological and geological heterogeneity makes the degree of benefit that CT has in different locations uncertain. In this study, the Soil and Water Assessment Tool (SWAT) was used to assess the impacts of changing IT for CT on nitrogen (N*)* and phosphorus (*P*) losses in surface water runoff from the potato crop in the Fuquene watershed. This is done at field and watershed levels. A two-year study quantified the changes in surface water runoff pollutants for three potato crop cycles under the traditional IT practice and CT practice - which included reducing tillage, green manure, and permanent soil cover - at twelve runoff plots installed in the Fuquene watershed (Quintero and Comerford, 2013). This information was used to build, calibrate and validate the SWAT model. The results suggest that CT for the Fuquene watershed can be reduced up to 26% of the sediment yield and 11% of the surface runoff compared with IT, which means an overall reduction of load. The main CT effect on nutrient losses in runoff is an increase in the total N and P (2% to 18% respectively) compared to IT. However, the results at watershed level showed different patterns from those obtained at field level. Despite the model uncertainties, the results show a possibility of using hydrological models to assess the effectiveness of various field management practices in agriculture.

Keywords:

Hydrological model; best management practice; conservation tillage; water quality; Andes; SWAT model.

1. Introduction

The decline in the water quality in the Fuquene watershed (Colombia) is a serious environmental problem, especially in Lake Fuquene, where an accelerated eutrophication process has been observed (Japan International Cooperation Agency—JICA, 2000). Nitrogen and phosphorus runoffs from potato crop fertilizer operations are estimated to be causing the increase of nutrients in the lake, which has in turn has increased the presence of algae bloom (Rubiano et al., 2006b). As a result, the biodiversity in the lake is threatened, as well that the drinking water for the local communities due to the leakage of toxic chemical in the treating process (Hanifzadeh et al., 2017), and also water for agriculture, fisheries and, particularly, for livestock (Quintero and Otero, 2006; Rubiano et al., 2006b). Therefore, the environmental authorities are aiming to address this problem due to the importance of this water source for the communities, agriculture and livestock (Rubiano et al., 2006a).

Intensive tillage (IT) is the conventional management practice used by potato farmers in the Fuquene watershed. This practice is characterized by a lack of plant coverage and low levels of crop residue in the potato cycle. Because of this, the soil is vulnerable to erosion processes and nutrient losses in the runoff (Zhang et al., 2014; Carter et al., 2009). Therefore, research nowadays focuses on agricultural BMPs which endeavor to use nutrients efficiently, conserve the soil structure and reduce runoff (Quintero and Comerford, 2013; Logan, 1993). In this context, agricultural BMPs that focus on non-tillage and reduced tillage are increasingly being adopted by farmers because they have the potential to reduce water pollution and to develop environmentally friendly agricultural systems, which at the same time will offer better income to local farmers (Liu et al., 2013; Sedano et al., 2013; Panagopoulos et al., 2011; Soane, 1990). Studies indicated that the BMPs in growing potato crops could reduce the loss of nutrients in surface without any negative effect on the potato yield and quality, although there may be some influence on the potato maturation and harvest date (Carter and Sanderson, 2001). A study done in 14 potato field trials at various locations across Idaho, Oregon over a time period of four years, demonstrated that potato farmers following BMPs received a similar yield with less financial investment than when following a maximum yield approach (Hopkins et al., 2007). Also, Zebarth and Rosen (2007) clarified that even when BMPs are developed to optimize tuber yield and reduce losses of nutrients, it is necessary to select the appropriate rate and timing for applying nitrogen-based fertilizers. In this way, it is possible to control potato growth according to the soil properties, water management, climatic conditions and terrain slope.

In Colombia, the regional environmental authority (Corporacion Autonoma Regional – CAR) in the Fuquene watershed has been investing in adopting conservation tillage (CT) since 1999 for the potato crop system. In this paper, CT is defined as any practice of soil cultivation that reduces runoff and increases infiltration by leaving the previous crop residues on the field (Derpsch, 2003). This also, increases the soil organic matter near the soil surface, improving the soil structure and biological properties in the potato crop (Carter et al., 2009). Experience has shown that CT provides potential benefits for organic matter increase, soil hydraulic properties, and that soil protection may be increased by the impact of rainfall (Carter and Sanderson, 2001). Nevertheless, the management effects of some biological properties are not measurable in the short term (i.e., less than 5 years) (Carter, 1992).

The International Center for Tropical Agriculture (CIAT) has been researching the impact on nutrient and soil losses in this crop since 2010 due to the implementation of CT practices in Fuquene watershed. Experimental runoff plots were installed, and the IT and CT practices applied. The specific CT practices adopted in the pilot project included reduced tillage, green manure, and a permanent soil cover crop prior to potato sowing. Sediment yield and loss of nitrogen (N) as NH_4^+ and NO_3^-, as well as phosphorus (P) as PO_4^{3-} in runoff were measured. The results helped to understand the effect of CT at field level. For example, Quintero and Comerford (2013) investigated the effect of CT in the potato crop system in the Fuquene watershed in order to assess the contribution of CT in potato-based rotations with respect to the aggregated soil organic carbon in the disturbed organic matter. The results indicated that reduced tillage in potato-based crop rotations increased the soil carbon concentration and average C content in the whole profile by 50 and 33% respectively, as compared to conventional farming practices. Thus, CT helps to bring these soils back to their original characteristics (high organic matter soils) (Quintero and Comerford, 2013).

Several studies report the effects of CT on pollutant losses by applying hydrological modeling tools. Many of these studies describe the accuracy of pollutant prediction obtained for each case study. However, the results are found to vary significantly and provide important insights only for particular agricultural watersheds (Park et al., 2014; Amon-Armah et al., 2013; Liu et al., 2013; Bosch et al., 2013; Betrie et al., 2011; Lam et al., 2011). Despite the increased use of modeling tools to assess the impact of CT as an agricultural BMP on the pollutant losses, there are still knowledge gaps in this topic. One of the most common issues identified to date is how to evaluate the effectiveness of BMPs at controlling nonpoint source pollution in order to obtain the necessary information that would help decision-makers to develop environmental regulations and manage the agricultural sector. Therefore, the objective of this research is to assess the impact of CT on sediments, nitrogen (N) and phosphorus (P) losses in runoff for potatoes at field and watershed levels by applying the Soil Water Assessment Tool (SWAT). This paper will contribute by answering the questions: How do the management practices in a potato-based mixed crop system influencing the runoff and soil nutrients (N and P) losses at the field and watershed levels? And, what would be the effect of applying CT extrapolation in current potato systems throughout all the watershed?.

2. Material and methods

Parameters related to the crop database, soil and agricultural management practices were set in the SWAT model according to the local crop systems. A calibration process was carried out by combining the data regarding the impact of management practices on soil and nutrient losses and runoff (measured in the field), and streamflow data from gauging stations. Usually, the calibration of the hydrological model calibration process is considered a challenge to be carry out in the Colombia watersheds, where the complexity of shifting cultivation, intensive traditional agriculture, diverse crops and management practices in a landscape, and weather seasonality are predominant. Also, CT management practices for the potato crop were extrapolated to be able to assess the whole basin. Additionally, the IT and CT effectiveness at field and watershed level were assessed in order to provide guidelines for the decision-makers and stakeholders who aim to use these agricultural management practices for the potato crop.

2.1 Fuquene watershed case study

This study was conducted on the Fuquene Lake watershed, located in the northern part of Bogota city (Colombia) (5°28′00″N, 73°45′00″W). The watershed has an area of approximately 784 km^2. The study area is characterized by large, rocky outcrops and mixed topography (flat areas, semi-flat and streams) which varies between 2,520 and 3,786 meters above sea level (m.a.s.l). The annual mean precipitation is 777.9 mm, and the annual temperatures are between 12 °C and 18 °C, without great variation throughout the year. The relative humidity ranges between 70% and 80% (IDEAM, 2004). The water from the lake is used and distributed by the municipal water supply companies for human consumption, in settlements located downstream of the lake. The water is supplied to more than 500,000 inhabitants of the region (IGAC, 2000). Fig. 1 presents the study area.

The development of agricultural activities in this watershed has become the main economic driver for its inhabitants. Due to the climate and soils, of this watershed, monocultures are predominant. The potato crop is considered as the most important crop in the watershed. It is worth mentioning that the potato crop has been included in the Food and Nutrition National Plan (PAN) as one of the main crops for the daily diet of millions of consumers, especially in low-income sectors (CAR, 2006). The potato-cultivated area in the Fuquene watershed is around 16,933 ha, with an annual production of 280,000 tons. Although the research uses the Fuquene Basin in Colombia as the main case study, the goal is to develop general methodologies that are applicable to similar watersheds.

2.2 Hydrological and water quality model

The watershed model used in this study was the Soil and Water Assessment Tool (SWAT) developed by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) (Arnold et al., 1998). The model is a continuous-time, semi-distributed, process-based river watershed-scale model, designed to simulate the long-term effects of water management decisions on the water quality and hydrology response (Neitsch et al., 2011). The model is built on a daily time step at sub-basin and watershed scales. The use of sub-basins in a simulation is particularly helpful when different areas of the watersheds are dominated by land uses or soils which are differ in their properties that may impact the hydrology. These are further subdivided into a series of Hydrological Response Units (HRU), which are common land areas within the sub-basin that are composed of unique land cover, soil and agricultural management practices (Arnold et al., 2012b). The hydrological cycle simulated is based on the water balance equation, which includes daily precipitation, runoff, evapotranspiration, percolation, and returns flow components (Gassman et al., 2007). Spatial information such as the soil type and characteristics, land use, climate, and topography are necessary inputs.

The input data required for this study were compiled from different sources. These include the Agustin Codazzi Geographic Institute (IGAC), the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM), the Regional Environmental Authority of Cundinamarca (CAR), and the public service companies. The resolution, scale, and sources are shown in Table 1.

The weather input data from 46 stations located in the basin were obtained from public and private institutions and provided by CAR (Fig. 1). The historic recorded daily data included: relative humidity, precipitation, temperature (maximum, minimum and average), solar radiation, and wind speed. Monthly flow measurements at the Boyera, El Pino, Puente Balsa and Puente Colorado stations were used to represent the flow in different locations of the watershed. The Puente Colorado station is located near the end of the basin and represents the outlet for the entire watershed just before the main river reaches the lake (Fig. 1). The Puente Balsa station has three months of empty records in 2008 and one month in the year 2013. Likewise, the Puente Colorado station did not record values for the years of 2006, 2008 and 2009. Therefore, these dates will not be used for the calculation of errors in the calibration and validation processes.

For this study, the SWAT model was built on a daily time step for the period 2006 to 2013. The watershed was delineated into 30 subbasins (Fig. 1). In the generation of HRUs, the slope classes were always set out in five ranges (0–5%; 5–15%; 15–25%; 25–45%; and >45%). The potential evapotranspiration (PET) was simulated using the Hargreaves method (Hargreaves and Samani, 1985) and the actual evapotranspiration (AET) was calculated based on the methodology developed by Ritchie (1972). In order to predict the surface runoff, The Natural Resources Conservation Service Curve Number (CN) method (USDA-SCS 1972) was used. CN values were determined based on a previous study, where the Colombian Land Cover map categories were associated with SWAT land cover codes (IDEAM et al., 2008).

2.3 Agricultural management practices

Agricultural management practices are inputs to the model by modifying the management files. The representation of the traditional and conservation potato agricultural management practices was simulated as scenarios. IT in the current situation corresponds to the baseline scenario, and the CT practice was considered to be scenario 1. Seven HRUs were selected because these correspond spatially with the plots installed in the field. These are characterized by being located in the subbasin 12 with mean slope 15% to 45%, and soil units MMVe3 and MMVg3 which are Inceptisol soil types classified by IGAC as Typic Haplustepts (IGAC, 2000).

Based on previous results from the experimental runoff plots installed in 2011 by CIAT in the municipality of Ubate located in the watershed, the parameter values related to management practices were defined (Quintero and Comerford, 2013; Quintero, 2014) (Fig. 1). The pilot Fuquene project established twelve experimental runoff plots - each with an area of 2,500 m^2 - for assessing two potato-based systems: conventional agriculture with intensive tillage (IT) and conservation agriculture with oat cover crop residues (green manure - GM), permanent cover and conservation tillage (CT). A total of three crop cycles were planted in September 2011, March 2012 and October 2012. The conventional agriculture with IT is traditionally a rotation between potato (Solanum tuberosum) and pasture (Lolium perenne) with grazing (Quintero, 2014). The IT operation is carried out by conventional plowing followed by rotovator passes to invert the soil (Fig. 2). On the other hand, the CT adopted in the pilot Fuquene project included different management practices such as reduced tillage, green manure, and permanent soil cover. The CT rotation (oats-potato-oats-potato-pasture) involved potatoes with an oat cover crop used as green manure prior to potato sowing, and pastures at the end of the rotation cycle (Quintero, 2014) (Fig. 3). The management practices parameter values obtained from the runoff plots are shown in Table 2. The physico–chemical characteristics of the soil measured in the field plots were defined in the soil database for the HRUs which correspond to the location of the runoff plots (Table 3).

2.4 Model calibration

Traditional statistical indicators measuring the proximity of the predictions to the observed values were used to evaluate the performance of SWAT: Nash–Sutcliffe efficiency index (NSE) (Eq. (1)), the index of agreement *d* (Eq. (2)), the root mean square error (RMSE) (Eq. (3)), and the mean absolute error (MAE) (Eq. (4)).

$$NSE = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2} \tag{1}$$

$$d = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \tag{2}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - P_i)^2} \tag{3}$$

$$MAE = N^{-1}\sum_{i=1}^{N}|O_i - P_i| \tag{4}$$

where: O_i = measured (observed) data, P_i = modeled data, $\bar{O}$ = mean of measured data, and N is the number of observations during the simulation period. NSE ranges between -∞ and 1.0 with NSE=1 being the optimal value, values between 0.0 and 1.0 being generally viewed as acceptable levels of performance, whereas values ≤0. 0 indicate that the mean observed value is a better predictor than simulated values, which indicates unacceptable performance (Nash and Sutcliffe, 1970). A computed *d* value of 1 indicates a perfect agreement between the measured and predicted values, and 0 indicates no agreement at all. RMSE and MAE values of 0 indicate a perfect fit.

Global sensitivity analysis was carried out with the aim of assessing the most sensitive parameters for setting up the model in this watershed. The built-in Latin hypercube one-at-a-time (LH-OAT) technique (Green and van Griensven, 2008; Morris, 1991) was used to determine the sensitive parameters for streamflow. The results obtained were used for flow calibration. Manual monthly calibration and validation were conducted using the data from the four stream gauging stations: Boyera, El Pino, Puente Balsa and Puente Colorado, compared with the outflows of subbasins 12, 7 and 2, respectively (Fig. 1). All these comparisons were based on the Nash–Sutcliffe efficiency index (NSE) (Eq. 1). The index of agreement *d*, the root mean square error (RMSE), and the mean absolute error (MAE), given by Equations (2) to (4), were used for each gauging station as a reference. Table 4 provides an overview of the parameters modified in the model calibration and their final calibration values.

The second step of the calibration process was for losses of sediments and nutrients. The model was calibrated manually using the monthly data from September 2011 to March 2013 for sediments, surface runoff, and concentration of soluble P, and NO_3 in the runoff. The mean absolute error (MAE) was used to evaluate the model performance for total accumulated sediment yield and nutrient losses, collected from each runoff plot during the mentioned period. Validation was conducted at field level with the results obtained in the HRUs where IT and CT practices were applied.

3. Results and discussion

3.1 Streamflow calibration

Sensitivity analysis was performed for streamflow to determine the most influential parameters on the model output. Table 4 presents the eleven most sensitive parameters related to streamflow from the 20 evaluated. The parameters were ranked according to the P-value (significance of the sensitivity) from the highest to the lowest, where the highest are the most sensitive parameters (Abbaspour et al., 2015). In general, Revapmn.gw (threshold water depth in the shallow aquifer for return flow by capillary and soil evaporation process), Gwqmn.gw (threshold water depth in the shallow aquifer required for return flow to occur), and Sol_k.sol (saturated hydraulic conductivity into the soil) were the most sensitive. The sensitivity analysis results were included in the streamflow model calibration. Table 5 presents the parameters that were adjusted in order to improve the efficiency of the model in the studied watershed for predicting the streamflow, which correspond mainly to runoff and groundwater flow processes.

The range of the simulation period was divided into two without including the first year. The first year was excluded because this time is the warm modeling period. The streamflow calibration process was performed for the first period (2006–2010) and the second period (2011–2013) was used for the validation process.. The calibration and validation results are summarized in Table 6. According to guidelines developed by Moriasi et al. (2007), the monthly streamflow calibration values at the four gauging stations were considered 'good' in the calibration period (NSE values greater than 0.65 and index of agreement (d) values were close to 1), with the exception of the Puente Balsa station (NSE = 0.5). The validation model predicted monthly flows at the four stations with NSE= 0.54, 0.32, 0.58 and 0.61, respectively, highlighting that values obtained at the El Pino station were considered unsatisfactory in the validation period (NSE=0.32). Fig. 4 shows the hydrographs for the calibration and validation results (the two periods separated by a red line) for each streamflow gauging station.

Overall, the monthly streamflow predictions were considered acceptable for this project. The baseflow is generally well represented by the model when compared to the observations. However, the peaks for certain times of the simulated period were slightly overpredicted. This is expected, considering that the watershed is under intensive agriculture, and the agricultural water used in the model was insufficient, since only the potato crop management was considered. Additionally, the calibration and validation were affected by the lack of information available on the “El Hato” reservoir (located upstream) and the dams constructed for irrigation. Similar findings have shown the overprediction of peak flows (Arnold et al., 2012; Harmel et al., 2014; Daggupati et al., 2015; Francesconi et al., 2016), which confirms that there is greater uncertainty in the calibration process, particularly for scenarios and case studies in which the information is not available.

3.2 Water quality calibration

On the other hand, calibration of nutrient losses in the runoff and sediments was performed for the available experimental period (September 2011 to March 2013) on the runoff plots related with the HRUs selected. Table 5 presents the parameters that were adjusted in order to improve the efficiency of the model in the studied watershed for the prediction of sediments and nutrients. In general, the calibration of the water quality for the IT management practices (baseline) was done by decreasing the sediment yield, increasing the content of NO_3^-, and decreasing soluble and organic P yields. Some important parameters are the CN2 defined for potato, which in the model database was increased by 10%, and the USLE_P (ratio of soil loss with a specific support practice), which was changed from 1 to 0.5 in order to reduce the sediment yield. In the case of the nutrients in the soil layer, the initial concentrations of NO_3^-, soluble P, organic N and P (Sol_no3, Sol_labp, Sol_orgn, and Sol_orgp) were defined according to the measurement obtained in the runoff plots.

The measured and simulated total (accumulated) values were compared for (i) the surface runoff, (ii) NO_3^-, (iii) the soluble P, and (iv) sediment losses, at field level (HRU analyzed). The calibration for sediments and nutrients was considered to be acceptable (Moriasi et al., 2007). The results (Table 7) showed that the highest absolute errors were calculated for surface runoff, with values of 1.5 and 2.3 l/m^2 for the IT and CT scenarios, respectively. However, the absolute error (Table 7) for the other variables was less than zero for each measurement unit. Despite the errors reported, a similar trend was observed for the IT and CT values simulated when compared with the field observations (runoff plots measurements). For instance, it can be observed that the total runoff and soil losses are reduced in the CT scenario, while the nitrogen and phosphorus concentrations in the runoff are higher, when compared to the intensive tillage (IT). However, the calibration can be further improved when continuous records of water quality parameters are available. Also, several calibration techniques have been developed for a physically based model like SWAT (Smarzyńska and Miatkowski, 2016; Me et al., 2015; Akhavan et al., 2010; Harmel et al., 2014; Arnold et al., 2012) and these could be suitable depending on the final goal of the modeling.

3.3 The effectiveness of CT-BMP at field level

The effectiveness of CT was first evaluated at field level. The period from September 2011 to February 2012 was selected for the assessment of the CT effect if compared to the baseline (IT) results obtained. This period was selected because it corresponds with the potato planting phase in both practices. In addition, CT spatial extrapolation was done for the whole potato crop area in order to define the impact on the water quality if BMPs were applied by all farmers (Fig. 1). Table 8 shows the results of the main effects of IT and CT on the average monthly runoff, sediment and nutrients in the runoff at field vs. watershed level.

The results for the CT practice showed a reduction of the sediment yield by 46%, and the surface runoff by 27% at field level (Table 8). The simulated sediment loads indicated a tendency to decrease when the surface runoff decreased, and the same tendency was found for soil loss, but not as high as for the sediment loads (Fig. 4). Furthermore, the soil loss reduction was almost twice the reduction of runoff during the rainy season. It is noteworthy that the percentage of runoff reduction (27%) is similar to the increase in infiltration obtained for CT, which varies from 429 mm H_2O to 553 mm H_2O (representing a 29% increase). Therefore, when the runoff is minimum and infiltration is maximum, there is a high possibility of water moving through the root zone (Stewart, 1994). Our study indicates that the soil–water content increase (approximately 3%) is in accordance with previous studies carried out in the same watershed (Quintero, 2009; Quintero and Comerford, 2013: Quintero, 2014). The trend of high infiltration as a consequence of CT practices is reported by other studies (Deubel et al., 2011; Ram et al., 2018; Villamil and Nafziger, 2015); however, it is stated that such results vary widely depending on the soil type, crop system, and management.

Additionally, the mass balances of nitrogen and phosphorus were analyzed in order to understand the differences between the effects of CT and IT practices on the nutrients losses. The mass balances showed that the total losses of N and P in the runoff increased by 17% and 29%, respectively. The total N and total P yields in the runoff at field level are shown in Fig. 6. The results at field level agree completely with the results from the data measured in the runoff plots reported by CIAT (Quintero et al., 2013; Quintero, 2014). The main reason for the total N and P increments is related to the increase of the organic N within a range of 50% and the increase of soluble P of 38% (Table 8). This might be attributed to the effect of the increase of the residual cover crop (oat as a green manure) in the potato–pasture rotation in the CT scenario.

The average concentration of nitrate-N in the runoff increased by 20% (Table 8) in the CT practice. Furthermore, this result was more evident in specific events. The transformation of fresh organic N to mineral N suggests an increase of up to 162 kg N/ha in the CT practice, compared with 47 kg N/ha in the IT practice. Mineralization of active nitrogen increases up to 248% in the CT, compared to IT. The mineralization of residual nitrogen, from fresh residual plants, to nitrate is about 80%, while active organic nitrogen is 20%. This means that mineralization generates a net gain in the nitrate due to oxidation of the N compounds, allowing nutrients to be released (Hart et al., 1994). The results for NO_3-leachate from the soil profile suggest that there is an increase of 15%. However, even though there is a high NO_3-N content in the soil, the model shows that it leaches, which prevents its accumulation in the soil profile. Consequently, there is a decrease by 10% of nitrogen uptake in the plants.

Despite the increase of the bulk density of the first soil layer (Table 3) and the decrease of the amount of surface runoff, the soluble phosphorus increased in the CT scenario (Table 8). The main reason for the soluble P increment may be that the amount of phosphorus in solution in the top 10 mm of soil increased by 26.88 kg P/ha, compared to 8.59 kg P/ha for the IT scenario. The results suggested that the increase of net P in solution can be attributed mainly to the mineralization of phosphorus from the fresh residue pool and from the active organic pool to the labile pool (P in solution), which increased by up to 178% in the CT, compared to IT. Deubel et al. (2011) reported an increase of soluble P by 24% under conservation tillage in long-term research, along with a trend of high P concentrations in deeper soil layers. In contrast, the implementation of CT can reduce by approximately 33% the organic phosphorus transported with the sediments into the reach (Table 8). The transformation of phosphorus between the mineral pool (P in solution) and the "active" mineral pool (P absorbed to the surface of soil particles) decreased by 69.85% in the CT scenario. Additionally, the decrease of the sediments yield (metric tons) for the CT scenario (Table 8) has a direct influence on the phosphorus load transported with sediments to the main channel in the surface runoff (Neitsch et al., 2011). Equally important, despite the increased availability of the total P and especially soluble P in this research, the uptake of P removed from the soil by plants was almost the same or even tended to be less for the CT scenario (38.63 and 36.86 kg P/ha for the IT and CT scenarios, respectively).

3.4 The effectiveness of CT-BMP at the watershed level

The extrapolation of the CT management practice was performed for the entire potato crop cultivated in the watershed, under different biophysical conditions (HRUs) from those evaluated at the field level. The results suggest that CT at the watershed level reduces the surface runoff and sediment yield by 11% and 26%, respectively. The reduction obtained for the two parameters represents approximately half of the reduction obtained at the field level. Furthermore, the greatest reduction in CT compared with IT occurred during the rainy season, which is when farmers normally perform fertilization tasks in order to take advantage of the wet soil conditions.

Surface runoff loss could be influenced by the tillage type and the rotation system (e.g., when incorporating green manure). However, the SCS runoff curve numbers (CN2) defined per soil type, land use, and management practices in the model inputs were not affected directly by the CT operation.

Therefore, the surface runoff increments cannot be attributed mainly to the CT scenario (Maharjan et al., 2018) . This is mainly because the precipitation, slope, and soil moisture vary for the other potato crop areas (HRUs) along the watershed, in addition to which the tillage practices affect the sediment yields. In the model, the P_{USLE} support practice factor (USLE_P) defined in the modified universal soil loss equation (William, 1995) is the only parameter related to CT practices that affects the sediment yields. However, to verify the consistency of this impact it is necessary to consider that the SWAT model is also directly affected by the surface runoff volume, topographic factors and soil erodibility factors defined in the soil properties.

Total nitrogen increased by 2% in the CT scenario at watershed level (Table 8). The concentration of nitrate-N was significantly higher in CT compared to IT, with an increase of 17% (Table 8). The increment in NO_3- was directly affected by the nitrification process, which oxidized the ammonia or ammonium coming from the inorganic fertilizer applied (0.26 and 4.42 kg N/ha in the IT and CT scenarios, respectively). Furthermore, no significant differences were shown for organic N (Table 8). This form of nitrogen is associated with the sediment loading, and consequently organic N decreases when the sediment loads are reduced. The amount of organic N transported to the main channel in surface runoff calculated by the model can be adjusted using the nitrogen enrichment ratio (ERORGN) parameter (Neitsch et al., 2011). In our study, the default value of the model was used, which is calculated by a logarithmic equation related to sediment concentration developed by Menzel (1980). Therefore, future studies are required to calibrate this parameter for the different types of soils in the watershed, and also to be able to calibrate the sediment loads for HRUs that are different from those used in the analysis at the field level.

In contrast, total phosphorus decreased by 18% in the CT scenario (Table 8). This effect is mainly due to the 38% decrease of soluble P in the surface runoff of the CT scenario in comparison to the IT scenario (Table 8). When each component of the phosphorus mass balance was analyzed, it was interesting to note that the amount of phosphorus between the "labile" mineral pool (P in solution) and the "active" mineral pool (P sorbed to the surface of soil particles) was -4.97 kg P/ha in the CT, compared to 3.87 kg P/ha in the IT scenario. A negative value in the model denotes a net gain in soluble P, due to the increase in the labile pool from the active pool (Neitsch et al., 2011). However, the amount of soluble P transported in surface runoff also depends on the bulk density of the first soil layer, and the phosphorus soil partitioning coefficient (PHOSKD), which is the ratio of the soluble P concentration in the surface soil to the soluble P concentration in surface runoff (Neitsch et al., 2011). For instance, even though the PHOSKD parameter was calibrated (Table 5) and the bulk density was measured (Table 3) at field level, the spatial transfer of the CT to a different type of soil affects directly the value calculated for the soluble P (Deubel et al., 2011) at the watershed level. Furthermore, the principal effect of the CT on organic P was a decrease of 8% compared to the IT scenario (Table 8). Unlike the organic N, the value obtained for the organic P showed a direct correlation with the sediment loading loss. Nevertheless, to verify the consistency of this impact over the watershed, the phosphorus enrichment ratio parameter (ERORGGP) calculated as a default by the model needs to be adjusted.

This study indicates that the use of an integrated watershed modeling to assess the impact of CT on nutrient properties requires further spatial calibration to improve the model accuracy. Farm-scale soil physical and chemical data under CT management is necessary to parameterize the inputs. For example, the soil bulk density in SWAT is an input defined manually by the user, and the temporal variation of the bulk density of the soil layer is not affected by the tillage operation (Arnold et al., 2012a; Maharjan et al., 2018). Although the impact of CT on the soil properties has been studied widely for the management of different crops over short- and long-term durations (Carter and Sanderson, 2001; Deubel et al., 2011; Ram et al., 2018; Quintero and Comerford, 2013; Villamil and Nafziger, 2015;

Wang et al., 2015), many gaps still need to be addressed, such as the simulation approach to soil tillage, and especially to the spatial and temporal changes of the soil's physical and microbial activity. However, we realize that some processes are difficult to characterize accurately in large watersheds due to the insufficient data or understanding of the processes themselves. Furthermore, depending on the research scope, the modeling approach may or may not be a viable alternative.

4. Conclusions and outlook

The objective of the study was to assess the impacts of CT on the runoff quality, as well as soil, nitrogen (N) and phosphorus (P) losses in a potato crop in the Fuquene watershed (Colombia) by applying the SWAT model. The model performance was calibrated and validated at field level for site-specific conditions, and then CT practices were extrapolated to the whole potato crop area in the basin. Despite the modeling uncertainties, the results provide evidence that the model-based approach presented is useful and effective, and it can be used as a strong basis to facilitate the development of land-use plans by local decision makers to reduce water pollution in the Fuquene watershed.

The results suggest that CT at the watershed level reduces the sediment yield by 26% and surface runoff by 11% if compared with IT, which means an overall reduction of load. The greatest reduction of CT occurs, especially in the rainy season. The main CT effect on nutrient losses in the runoff is that an increase occurs in the total N and P (2% to 18% respectively) compared to the baseline. In addition, the CT simulation results suggest that the concentration of N- NO3- in the surface runoff could be increased by 17%. This might be attributed to the nitrification process, which oxidized the ammonia or ammonium coming from the inorganic fertilizer applied. However, the results at watershed level showed different patterns from those obtained at field level. In fact, the major limitation identified in this study arises from the process of the CT extrapolation practice for all the potato crop areas within the watershed, because the calibration model was made for a very small area (field level), and the initial and calibrated parameter values are the same for other soil types and average slopes.

This paper provides important information about the effects of potato crop agricultural management practices on the runoff water quality in an Andean watershed. It thereby provides a potential model for future Andean watershed studies, providing guidelines to decision-makers and stakeholders who are aiming to use these agricultural management practices for the potato crop. Given the loss of nutrients obtained for the CT practice, the authors suggest that it may be possible to reduce the amounts applied, considering the contribution of the green manure nutrients involved. Adjusting to the amounts of fertilizer could help increase the competitiveness of conservation agriculture in potato crops, compared to conventional management practices. However, it is necessary to assess reduced dose trials and their impacts on productivity, erosion, and runoff. In addition, more detailed spatio-temporal models and the application of optimization techniques would be a very useful approach to identify and allocate CT-BMP options with the aim of reducing the reliance of agricultural practices on water pollution. Moreover, using this type of models and techniques, it could be possible to include several crops in the same watershed, consider climate change scenarios, and define suitable parameters for the different areas in the watershed. Overall, future research that contemplates these points will help mitigate the uncertainty in assessing the implementation of BMPs at the watershed level.

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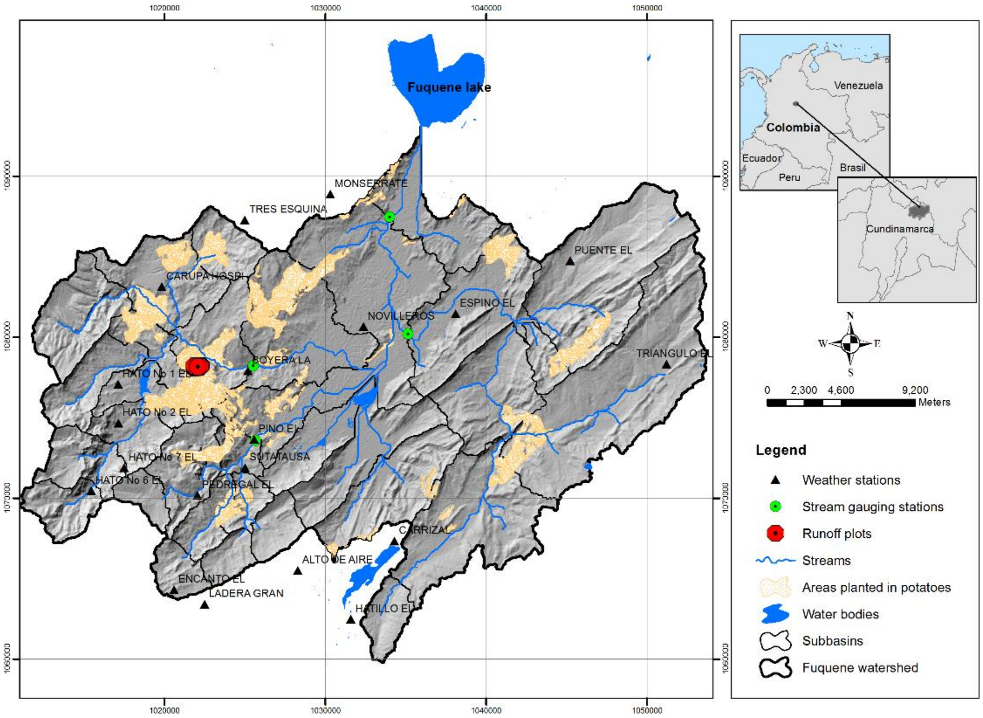


Fig. 1. Location of the Fuquene watershed in Colombia, the location of stream gauging and weather stations in the watershed, runoff plots location, and subbasin delineation defined in SWAT modeling.

Table 1

Spatial input data

Data type	Resolution	Source
Topographic map	30m	CAR
Land use map	1:25.000	IGAC
Soil map	1:100.000	IGAC
Weather	No. of stations: 21	CAR-IDEAM

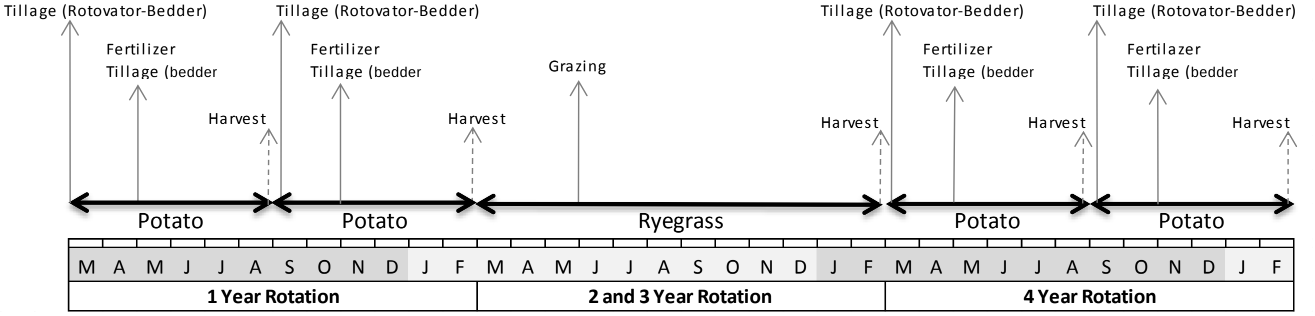


Fig. 2. A conceptual outline of conventional (IT) potato crop management practices.

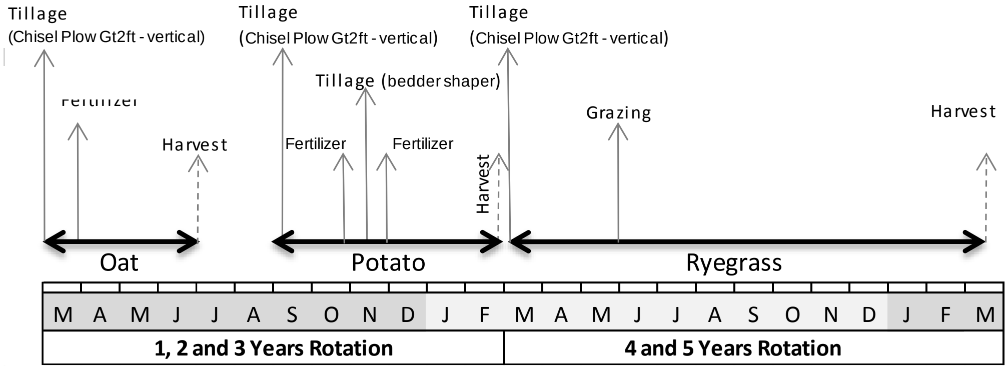


Fig. 3. A conceptual outline of conservational (CT) potato crop management practices.

Table 2

Parameter values defined related management practices per scenario.

Variable name	Definition	Value				
		IT		CT		
Planting		**POTA**	**PASTURE**	**POTA**	**OAT**	**PASTURE**
PLANT_ID	Plant/land cover code from crop.dat	POTA	RYEG	POTA	OATS	RYEG
HEAT UNITS	PHU: Total heat units required for plant maturity	800	700	800	400	700
BIO_INIT	Initial dry weight biomass (kg/ha)	200		200	18	
HI_TARG	Target harvest index					
BIO_TARG	Biomass (dry weight) target (metric tons/ha)					
CN2	Initial SCS runoff curve number (min 35- max 98)	62	40	62	53	40
Grazing						
MANURE_ID	Manure code from fert.dat		Beef-Fresh			Urea
GRZ_DAYS	Number of days of grazing		200			200
BIO_EAT	Dry weight plant biomass consumed daily (kg/ha)		30			30
BIO_TRMP	Dry weight of biomass trampled daily ((kg/ha)/day)		14			14
MANURE_KG	Amount of manure applied -dry weight (kg/ha)		6			6
BIO_MIN	Minimum plant biomass for grazing to occur (kg/ha)		500			500
Tillage						
TILLAGE_ID	Tillage implementation	Bedder shaper	Rotovator-bedder	Chisel Plow Gt2ft -vertical		Bedder shaper
EFFMIX	Mixing efficiency of tillage operation (fraction)	0.55	0.8	0.3		0.55
DEPTIL	Depth of mixing by tillage operation (mm)	150	100	150		150
BIOMIX	Biological mixing efficiency (fraction)	0.2	0.2	0.2	0.2	0.2
Fertilizer						
FERT_ID	Type of fertilizer/manure applied	13-26-06		13-26-06	Urea	
FRT_KG	Amount of fertilizer/manure applied (kg/ha)	1400 (2 times of 700 each one)		1000 (2 times of 500 each one)	300	
FRT_ SURFACE	The fraction of fertilizer applied to top 10 mm	1		1	1	

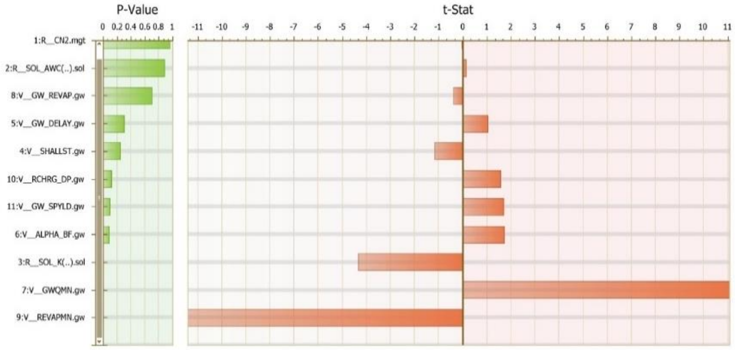
Table 3

Physico-chemical soil parameters measured in the field plots defined in the selected HRUs.

Treatment	Soil profile	Depth (cm)	Bulk density (g/cm^3)	Soil available water content (mm/mm)	Hydraulic conductivity (mm/h)	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	Carbon (%)
IT	A	0 - 40	1.39	0.140	109.16	32.32	51.84	15.84	3.02	3.05
	B	40 - 60	1.58	0.160	76.30	32.60	50.35	17.05	1.16	0.57
CT	A	0 - 20	1.29	0.270	203.14	6.45	66.13	27.42	8.50	3.74
	B	20 - 40	1.29	0.420	101.07	24.62	37.88	37.50	5.89	2.59

Table 4

Sensitivity analysis rank results for streamflow model output.

Rank	Parameter[a]	*t*-value[b]	*p*-value[c]	
1	r_Cn2.mgt	-0.014	0.989	
2	r_Sol_awc( ).sol	0.040	0.968	
3	v_Gw_revap.gw	-0.391	0.737	
4	v_Gw_delay.gw	1.009	0.313	
5	v_Shallst.gw	-1.134	0.210	
6	v_Rchrg_dp.gw	1.617	0.183	
7	v_Gw_spyld.gw	1.877	0.107	
8	v_Alpha_bf.gw	-4.381	0.099	
9	r_Sol_K( ).sol	-4.348	0.016	
10	v_Gwqmn.gw	11.254	0.005	
11	v_Revapmn.gw	-11.051	0.000	

[a] v: parameter value is replaced by a value from the given range; r: parameter value is multiplied by (1 + a given value) (Abbaspour et al., 2007).

[b] *t*-value shows a measure of sensitivity: the larger the *t*-value are more sensitive.

[c] *p*-value shows the significance of the sensitivity: the smaller the p-value, the less chance of a parameter being by chance assigned as sensitive

Table 5

Streamflow, sediment and nutrients parameters, allowable ranges, and final calibration values.

Parameter	Description in SWAT	Range	Model default value	Final value
Streamflow				
ALPHA_BF	Baseflow alpha factor [days].	0 – 1	0.048	0.02
GW_DELAY	Groundwater delay [days].	0 – 500	31	25
GW_REVAP	Groundwater revap coefficient.	0 – 1	0.02	0.02
RCHRG_DP	Deep aquifer percolation fraction.	0 – 1	0.05	0.1
REVAPMN	Threshold water depth in the shallow aquifer for revap [mm].	0 – 500	1	100
GWQMN	Threshold water depth in shallow aquifer for flow [mm].	0 - 5000	0	100
SHALLST	Initial depth of water in the shallow aquifer [mm].	0 - 1000	0.5	100
GW_SPYLD	Specific yield of the shallow aquifer [m^3/m^3].	0 - 0.4	0.003	0.2
GWHT	Initial groundwater height [m].	0 – 40**	1	25
CN2	Initial SCS CN II value.	35 – 98	Specific to HRU	
SOL_K	Saturated hydraulic conductivity [mm/h].	0 - 2000	Specific to soil survey unit	
SOL_AWC	Available water capacity [mm H$_2$0/mm soil].	0 – 1		
Sediment				
BIOMIX	Biological mixing efficiency.	0 – 1	0.2	0.2
CN2	SCS runoff curve number for moisture condition II.	35 – 98	Specific to land use	0.1*CN2$_{default}$
USLE_P	USLE equation support practices.	0 – 1	1	0.5
SLSUBBSN	Average slope length.	10 - 150	Specific to HRU	0.1*SLSUBBSN$_{default}$
Crop growth				
T_OPT	Optimal temp for plant growth.	Nov-38	22	17
T_BASE	Min temp plant growth.	0 – 18	7	5
HEATUNITS	Total heat units for cover/plant to reach maturity.	0 - 3500	1800	800*
Nutrients				
PHOSKD	Phosphorus soil partitioning coefficient.	100 - 300**	175	200
NPERCO	Nitrogen percolation coefficient.	0 – 1	0.2	1
RSDCO	Residue decomposition coefficient.	0.02 - 0.1	0.05	0.1
SOL_LABP	Initial soluble P concentration in surface soil layer [mg/kg].	0 – 100	0	44
SOL_NO3	Initial NO$_3$ concentration in soil layer [mg/kg].	0 – 100	0	12
SOL_ORGN	Initial organic N concentration in soil layer [mg/kg].	0 – 100	0	10
SOL_ORGP	Initial organic P concentration in surface soil layer [mg/kg].	0 – 100	0	10
PPERCO_SUB	Phosphorus percolation coefficient.	10 -17.5	10	17
BIO_TARG	Biomass (dry weight) target [metric ton/ha].	4 – 100	0	30
FRT_SURFACE	Fraction of fertilizer applied to top 10mm of soil.	0 – 1	0	1

* Value calculated with local weather using PHU_program available at SWAT webpage (http://swat.tamu.edu/software/potential-heat-unit-program/).

**The maximum was adjusted for the case study.

Table 6
Calibration and validation flow performances at the watershed level.

Catchment station	CALIBRATION						VALIDATION					
	Flow rate (m$_3$/s)		NSE	d	RMSE	MAE	Flow rate (m$_3$/s)		NSE	d	RMSE	MAE
	Simulated	Observed					Simulated	Observed				
La Boyera	1.5	1.41	0.78	0.94	0.6	0.45	1.6	1.32	0.54	0.9	0.59	0.41
El Pino	0.52	0.43	0.61	0.9	0.28	0.21	0.42	0.32	0.32	0.87	0.2	0.15
Pte. La Balsa	1.58	1.38	0.50	0.88	0.79	0.62	2.03	1.45	0.58	0.87	0.78	0.66
Pte. Colorado	3.58	3.85	0.68	0.88	1.68	1.3	4.6	3.87	0.61	0.87	2.26	1.79

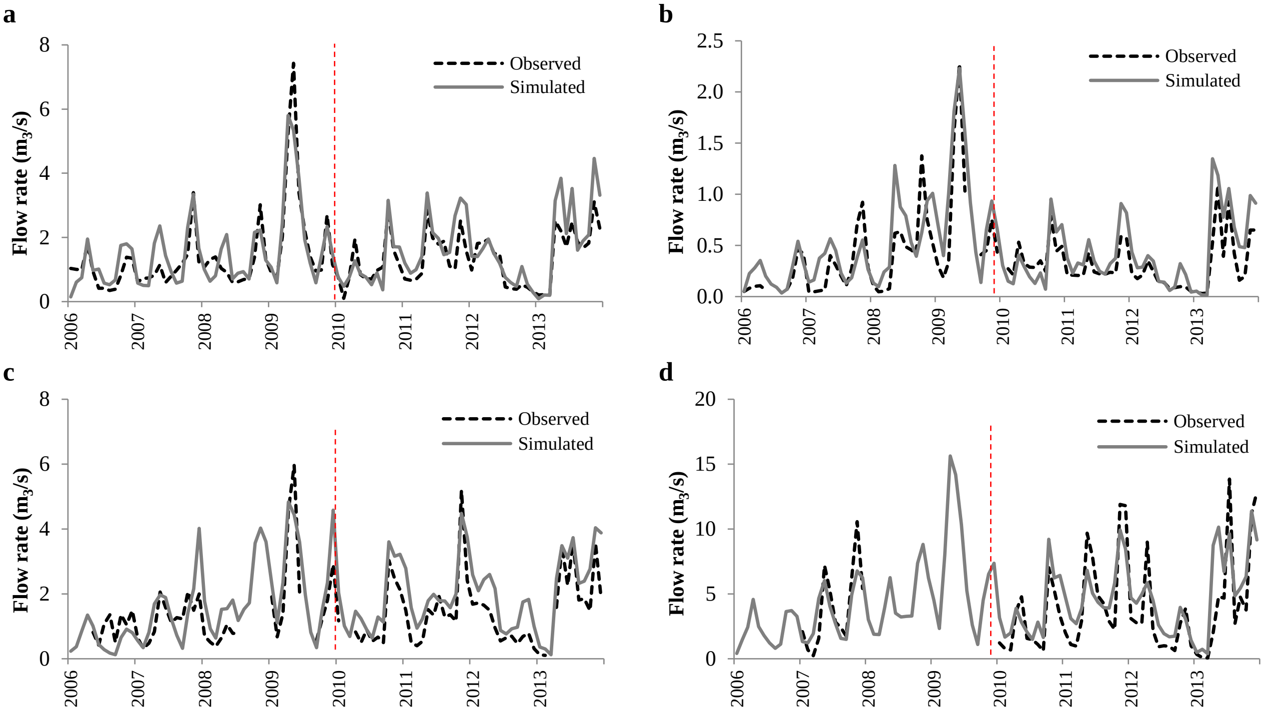


Fig. 4. Monthly calibration and validation results for flow (**a**) La Boyera, (**b**) El Pino (**c**) Pte. Balsa, and (**d**) Pte. Colorado.

Table 7
Sediment and nutrient losses performance.

Variable**	Measured		Simulated		Ɛ*	
	IT	CT	IT	CT	IT	CT
Runoff water						
Surface runoff (l/m_2)	27.45	26.05	28.97	24.03	1.53	-2.01
NO_3^- in surface runoff (kg N/ha)	0.68	0.72	0.39	0.47	-0.29	-0.25
Soluble P yield (kg P/ha)	0.18	0.20	0.21	0.29	0.03	0.08
Sediments						
Sediment yield (T/ha)	0.62	0.07	0.58	0.31	-0.04	0.25

* **Ɛ**: Absolute error. ** Accumulated total values from September 2011 to March 2013.

Table 8
The main effects of IT and CT on average monthly runoff, sediment, and nutrients in surface runoff.

Variable	**Field-level**			**Watershed-level**		
	IT	**CT**	**Difference (%)**	**IT**	**CT**	**Difference (%)**
Surface runoff (l/m_2)	32.84	24.03	-26.83	15.91	14.13	-11.19
Sediment yield (ton/ha)	0.58	0.31	-46.55	1.89	1.4	-25.93
Nitrogen losses (kg/ha)						
Total N loss	221.15	258.05	16.69	21.33	21.71	1.78
Organic N	0.08	0.12	50.00	3.36	3.38	0.59
Nitrate surface runoff	0.39	0.47	20.51	0.53	0.62	16.98
Nitrate leached	166.65	191.16	14.71	9.22	9.43	2.28
Nitrate lateral flow	4	4.85	21.25	6.03	6.11	1.33
Nitrate groundwater yield	50.03	61.46	22.85	2.17	2.2	1.38
Phosphorus losses (kg/ha)						
Total P loss	0.24	0.31	29.17	0.77	0.63	-18.18
Organic P	0.03	0.02	-33.33	0.49	0.45	-8.16
Soluble P	0.21	0.29	38.10	0.29	0.18	-37.93

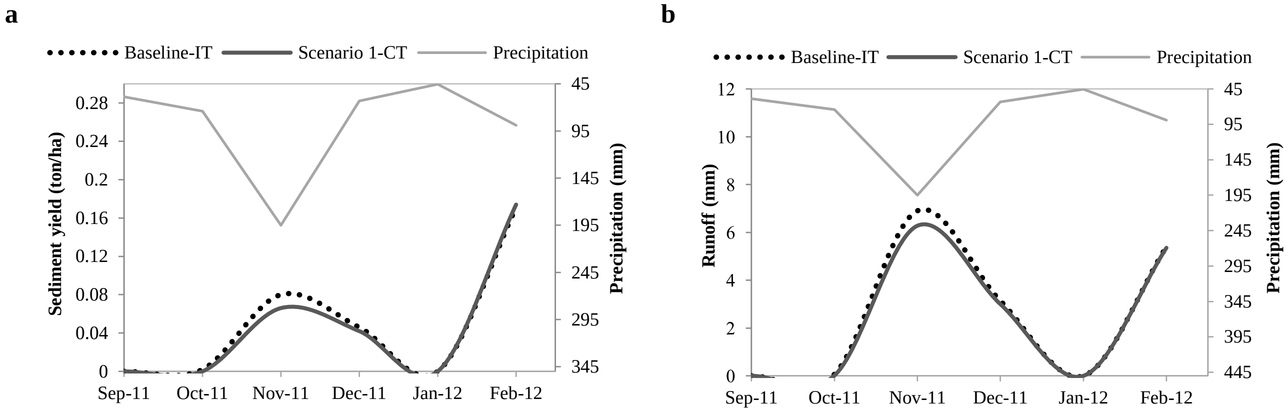


Fig. 5. Sediment losses (**a**) and runoff (**b**) at field level - right vertical axes.

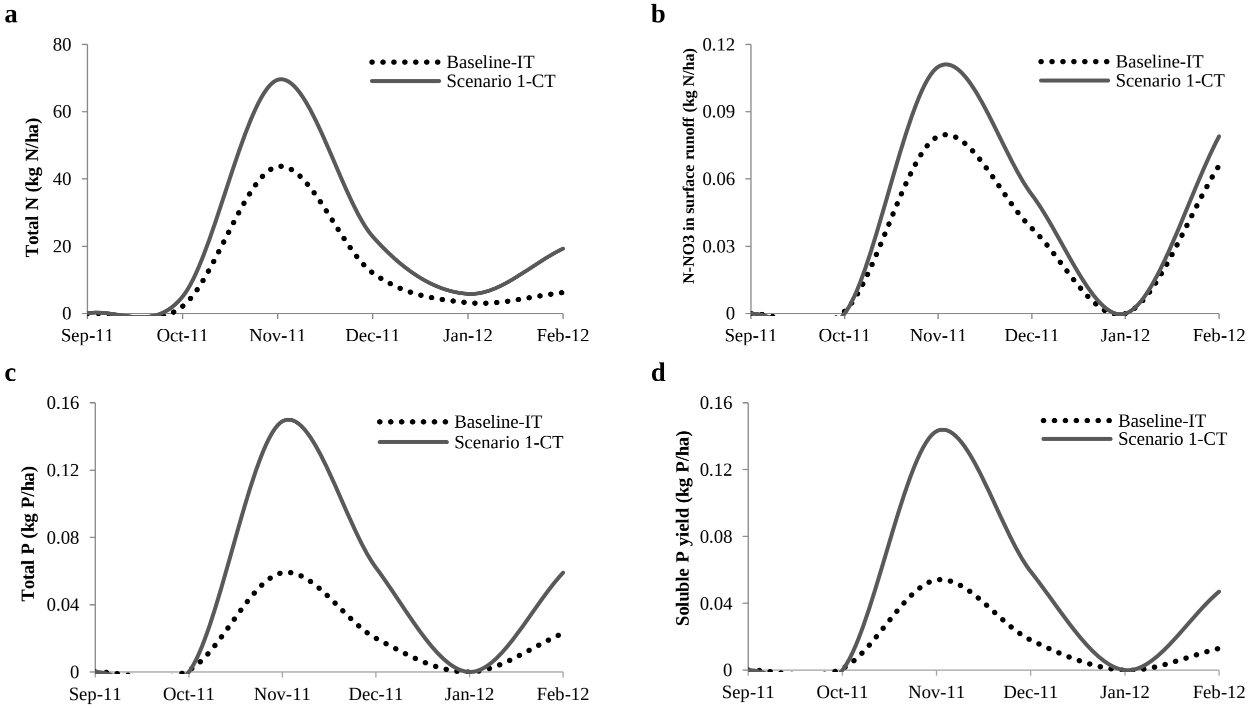


Fig. 6. Monthly total N (**a**), total P (**b**), N-NO3 (**c**), and soluble P (**d**) in surface runoff at field level.